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Date: February 20, 1998

Attorney
Docket No.: CSDL1-453AXFirst Named Inventor or
Application Identifier: Jonathan J.
Bernstein

02/20/98
JESSI UNITED STATES PATENT APPLICATION
Patent Commissioner for Patents
Washington, D.C. 20231

Sir:

Transmitted herewith under 37 CFR § 1.53(b) for filing is the **patent application** of:

Inventor: Jonathan J. Bernstein

Entitled: **METHOD FOR FABRICATING A TUNNELING SENSOR WITH LINEAR FORCE REBALANCE**

[X] This is a Request for filing a [] **continuation** [X] **divisional** [] **continuation-in-part** application under § 1.53(b) of prior Application No. 08/694,333, filed August 8, 1996 entitled:

TUNNELING SENSOR WITH LINEAR FORCE REBALANCE AND METHOD FOR FABRICATING THE SAME

Enclosed are:

[X] 23 pages of written description, claims and Abstract, inclusive

[X] 6 sheets of informal drawings consisting of Figs. 1-12 (one set)

[X] Oath or Declaration

[] Newly executed (original or copy)

[X] Copy from prior application (37 CFR 1.63(d)) (for continuation/divisional). The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.

[] To be filed later

[] Cover sheet and Assignment of the invention to:

[] Certified copy of a _____ application (if foreign priority is claimed) with letter claiming priority under Rule 55

[X] Information Disclosure Statement with 12 citations. Copies of citations were submitted in parent case.

[] Preliminary amendment is enclosed

[X] Return receipt postcard

[] Other:

[X] Verified statement was filed in prior application. Status still proper and desired.

TRANSMITTAL FORM FOR FILING PATENT APPLICATION (CONTINUED)

Attorney
Docket No.: CSDL1-453AX

- ☒ Priority is claimed under 35 USC § 120 as indicated on the attached sheet 4.
☐ Priority is claimed under 35 USC § 119(a)-(d) as indicated on the attached sheet 4.
☐ Priority is claimed under 35 USC § 119(e) as indicated on the attached sheet 4.

☐ _____ is hereby appointed Associate Attorney by:
 Registration No.:

 Attorney of Record:
 Registration No.:

- ☐ **Power of Attorney** in the originally-filed application has been granted to one or more of the registered attorneys listed below. The attorneys listed below not previously granted power in the originally-filed application, as well as _____, are hereby given associate power: _____
 Registration No.:

Stanley M. Schurgin, Reg. No. 20,979
 Charles L. Gagnebin III, Reg. No. 25,467
 Paul J. Hayes, Reg. No. 28,307
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 Beverly E. Hjorth, Reg. No. 32,033
 Holliday C. Heine, Reg. No. 34,346
 Gordon R. Moriarty, Reg. No. 38,973

1. ☒ Cancel in this application original claims 1-17 of the prior application before calculating the filing fee. (At least one original independent claim must be retained for filing purposes.)
 2. ☐ Add in this application claims _____ per amendment before calculating the filing fee.

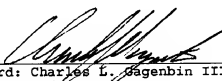
CLAIMS FILED:	MINUS BASE:	EXTRA CLAIMS:	RATE:	BASIC FEE:
				\$790.00
Independent	1 - 3	= 0	x \$82.00 =	-0-
Total	7 - 20	= 0	x \$22.00 =	-0-
<input type="checkbox"/> Multiple Dependent Claims (1st presentation)			+ \$270.00 =	-0-
SUBTOTAL FILING FEE				\$790.00
Small Entity filing, divide by 2. (Note: verified statement must be attached per \$1.9, \$1.27, \$1.28.)				\$395.00
TOTAL FILING FEE				\$395.00

- ☒ The filing fee has been calculated above; a check in the amount of \$395.00 is enclosed.
☐ The filing fee will be submitted at a later date.

TRANSMITTAL FORM FOR FILING PATENT APPLICATION (CONTINUED)

Attorney
Docket No.: CSDL1-453AX

- [X] In the event a Petition for Extension of Time under 37 CFR §1.17 is required by this paper and not otherwise provided, such Petition is hereby made and authorization is provided herewith to charge Deposit Account No. 23-0804 for the cost of such extension.
- [X] The Commissioner is hereby authorized to charge payment of any additional filing fees under 37 CFR §1.16 associated with this communication or credit any overpayment to Deposit Account No. 23-0804. Note, unless the adjacent box is X'd, no authorization is hereby given to charge additional fees under §1.16.



Attorney of Record: Charles L. Gagenbin III
Registration No.: 25,467

SUBMIT IN TRIPLICATE

TRANSMITTAL FORM FOR FILING PATENT APPLICATION (CONTINUED)Attorney
Docket No.: CSDL1-453AX

- ☒ Priority is claimed under 35 USC § 120 of prior Application
No. 08/694,333, filed August 8, 1996, entitled:

TUNNELING SENSOR WITH LINEAR FORCE REBALANCE AND METHOD FOR FABRICATING THE SAME

- ☒ The above-identified application is assigned
of record to: THE CHARLES STARK DRAPER LABORATORY, INC

- ☐ Priority is claimed under 35 USC § 119(a)-(d) of the following application(s).

(Application Number)	(Country)	(Filing Date)
(Application Number)	(Country)	(Filing Date)
(Application Number)	(Country)	(Filing Date)
(Application Number)	(Country)	(Filing Date)

- ☐ The above-identified application(s) is/are assigned
of record to:

- ☐ Priority is claimed under 35 USC § 119(e) of the following provisional application(s).

(Application Number)	(Filing Date)
(Application Number)	(Filing Date)
(Application Number)	(Filing Date)
(Application Number)	(Filing Date)

- ☐ The above-identified provisional application(s) is/are assigned
of record to:
- ☐ The claim to small entity status in the above-identified provisional application(s)
is made in this application and a copy of the Small Entity form(s) from the
provisional application(s) is/are enclosed.

116604

1 FIELD OF INVENTION

2 The present invention relates generally to tunneling sensors
3 and, more particularly, to a tunneling sensor with linear force
4 rebalance and a method for fabricating the same.

5
6 BACKGROUND OF THE INVENTION

7 Some former force rebalance tunneling sensors used a single
8 capacitor with a square law volts-to-force relationship. This
9 yielded an output voltage proportional to the square root of the
10 quantity to be measured. Alternative former force rebalance
11 tunneling sensors used piezoelectric layers to perform the
12 rebalance function.

13 Sensors providing a non-linear output are generally
14 undesirable because they lead to harmonic distortion of the
15 quantity being measured. Sensitivity also varies with the
16 magnitude of input signals. Furthermore, the dynamic range over
17 which a sensor yields a faithful representation of an input
18 signal is reduced.

19 Piezoelectric rebalancing is generally inferior due to
20 hysteresis, poor temperature and time stability, and small
21 available displacements. The additional complexity of
22 fabricating piezoelectric layers on a micromachined device is
23 also undesirable.

24 On the other hand, linear force rebalancing increases
25 dynamic range and reduces non-linearity, harmonic distortion, and

1 intermodulation distortion. For many applications, such as
2 phased arrays, linear operation is absolutely essential.

3 NASA's Jet Propulsion Laboratory (JPL) has designed a state
4 of the art tunneling accelerometer device primarily for use in
5 phased arrays (see "Tunnel-Effect Displacement Sensor", NASA Tech
6 Briefs, Vol. 13, No. 9, September 1989), but this device has
7 several minor drawbacks that may act as barriers to practical
8 use. For instance, the JPL device requires a high bias voltage.
9 Specifically, the JPL device currently requires a 200 volt bias
10 voltage to close the gap between the tunnel-effect tip. This
11 large voltage is necessary because of a large capacitor gap
12 (hundreds of microns) in the rebalance capacitor. This is an
13 uncommonly high voltage for use in towed arrays, inasmuch as high
14 voltages create corrosion and safety hazards in handling and
15 testing. Furthermore, the circuitry required to generate such a
16 high voltage can generate noise for the rest of the array.

17 Another drawback of the JPL device is that it employs non-
18 linear force rebalance. A single capacitor is used for force
19 rebalance in the JPL device, and the force across this single
20 capacitor is proportional to the square of the applied voltage.
21 This puts a non-linearity in the feedback loop wherein the output
22 voltage is proportional to the square root of the incident
23 acceleration. This, in turn, creates harmonic distortion,
24 intermodulation, and phase non-linearity, which leads to reduced
25 sensitivity and dynamic range. For array applications,

1 linearity, uniform phase, and low distortion are essential to the
2 combining of the numerous transducers which make up the array.

3 Still another drawback of the JPL device is its size, which
4 is on the order of 8 mm. This is fairly large for a
5 micromachined sensor. For many applications, such as thin line
6 towed arrays, this is simply too large.

7 Accordingly, it would be desirable to overcome the
8 disadvantages of former force rebalance tunneling sensors and
9 thereby provide a tunneling sensor having a pair of force
10 rebalance capacitors that are used in a push-pull relationship so
11 as to provide a rebalance force that is a linear function of
12 applied rebalance voltages, which leads to an output torque
13 voltage that is linearly related to input acceleration.

14 SUMMARY OF THE INVENTION

15
16 The present invention contemplates a tunneling sensor having
17 a pair of force rebalance capacitors that are used in a push-pull
18 relationship so as to provide a rebalance force that is a linear
19 function of applied rebalance voltages, which leads to an output
20 torque voltage that is linearly related to input acceleration.

21 The present invention tunneling sensor, which is constructed
22 primarily as a rotational accelerometer, comprises a plate
23 electrode that is formed from and attached to a silicon substrate
24 by a pair of torsional flexures, which provide an axis of
25 rotation for the plate electrode. A pendulous mass is formed on
26 a first end of the plate electrode, and a tunnel-effect contact

1 is formed on a second end of the plate electrode. A pair of
2 torque rebalance bridge electrodes are formed on the substrate so
3 as to span the plate electrode. A tunnel-effect tip is formed on
4 the substrate so as to be proximate the tunnel-effect contact and
5 in line with the rotational path that the tunnel-effect contact
6 takes when the plate electrode is rotated.

7 The plate electrode, and hence the tunnel-effect contact,
8 are typically grounded, while the pair of torque rebalance bridge
9 electrodes are complementarily driven with rebalance voltages,
10 having a constant bias voltage component and a output torque
11 voltage component, so as to generate an electrostatic rebalance
12 force that is a linear function of the rebalance voltages. A
13 small bias voltage is typically applied to the tunnel-effect tip
14 so as to induce the tunnel current. The result is an output
15 torque voltage that is linearly related to input acceleration.

16 Accordingly, the primary object of the present invention is
17 to provide a tunneling sensor having a pair of force rebalance
18 capacitors that are used in a push-pull relationship so as to
19 provide a rebalance force that is a linear function of applied
20 rebalance voltages, which leads to an output torque voltage that
21 is linearly related to input acceleration.

22 The above primary object, as well as other objects,
23 features, and advantages, of the present invention will become
24 readily apparent from the following detailed description which is
25 to be read in conjunction with the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to facilitate a fuller understanding of the present invention, reference is now made to the appended drawings. These drawings should not be construed as limiting the present invention, but are intended to be exemplary only.

Figure 1 is a plan view of a tunneling sensor with linear force rebalance according to the present invention;

Figure 2 is a schematic block diagram of a control system for the tunneling sensor shown in Figure 1;

Figure 3 is a cross-sectional side view, taken in relation to line A-A of Figure 1, of a tunneling sensor according to the present invention in its initial fabrication stage;

Figure 4 is a cross-sectional side view, taken in relation to line A-A of Figure 1, of the tunneling sensor shown in Figure 3 after the initial oxide layer has been patterned on both its front and back sides;

Figure 5 is a cross-sectional side view, taken in relation to line A-A of Figure 1, of the tunneling sensor shown in Figure 4 after a boron diffusion has been performed on the silicon wafer through the patterned openings in the initial oxide;

Figure 6 is a cross-sectional side view, taken in relation to line A-A of Figure 1, of the tunneling sensor shown in Figure 5 after the initial oxide has been photolithographically removed from certain regions thereof;

1 Figure 7 is a cross-sectional side view, taken in relation
2 to line A-A of Figure 1, of the tunneling sensor shown in Figure
3 6 after a sacrificial (spacer) layer has been deposited on
4 selected patterned regions;

5 Figure 8 is a cross-sectional side view, taken in relation
6 to line A-A of Figure 1, of the tunneling sensor shown in Figure
7 7 after a thin metal (seed) layer has been deposited thereon;

8 Figure 9 is a cross-sectional side view, taken in relation
9 to line A-A of Figure 1, of the tunneling sensor shown in Figure
10 8 after an electroplating mask has been deposited and patterned
11 thereon;

12 Figure 10 is a cross-sectional side view, taken in relation
13 to line A-A of Figure 1, of the tunneling sensor shown in Figure
14 9 after a pendulous weight, bridge electrodes, and a tunnel tip
15 have been electroplated in the open areas of the electroplating
16 mask;

17 Figure 11 is a cross-sectional side view, taken in relation
18 to line A-A of Figure 1, of the tunneling sensor shown in Figure
19 10 after the electroplating mask, the sacrificial (spacer) layer,
20 and the exposed portions of the thin metal (seed) layer have been
21 removed by polymer stripping;

22 Figure 12 is a cross-sectional side view, taken in relation
23 to line A-A of Figure 1, of the tunneling sensor shown in Figure
24 11 after an anisotropic EDP etch (ethylene-diamine, pyrocatechol,
25 and water) is preformed to substantially free up the plate
26 electrode.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Referring to Figure 1, there is shown a plan view of a tunneling sensor 10 with linear force rebalance according to the present invention. The present invention tunneling sensor 10, which is constructed primarily as a rotational accelerometer, comprises a plate electrode 12 that is formed from and attached to a substrate 14 by a pair of torsional flexures 16 that provide an axis of rotation about which the plate electrode 12 is rotatable. The plate electrode 12 and the pair of torsional flexures 16 are typically etched out from the substrate 14, as indicated by the etch slot 32 shown in Figure 1 (also see Figure 12) and as will be described in detail below.

A pendulous mass 18 is formed on a first end of the plate electrode 12, and a tunnel-effect contact 20 is formed on a second end of the plate electrode 12. A pair of torque rebalance bridge electrodes 22 are formed on the substrate 14 so as to span the plate electrode 12 (see Figure 12). A tunnel-effect tip 24 is formed on the substrate 14 so as to be proximate the tunnel-effect contact 20 and in line with the rotational path that the tunnel-effect contact 20 takes when the plate electrode 12 is rotated. It should be noted that the pendulous mass 18 and the tunnel-effect contact 20 may be formed on the same end of the plate electrode 12 if such is adjusted for in the applied rebalance voltages, as described in detail below.

The plate electrode 12, through one of the pair of torsional flexures 16, each of the pair of torque rebalance bridge

electrodes 22, and the tunnel-effect tip 24 all have associated electrically conductive contacts 26, 28, and 30, respectively, so as to allow for wire bonding during packaging.

At this point it should be noted that the substrate 14 is typically bulk silicon and the plate electrode 12 is typically a boron diffused portion thereof, as is described in detail below. The pair of torsional flexures 16 are included as part of the boron diffused area, as indicated by the shaded area shown in Figure 1. The pendulous mass 18, the pair of torque rebalance bridge electrodes 22, and the tunnel-effect tip 24 are all typically electroplated gold, or an electroplated gold layer covered by another electroplated metal, as is also described in detail below. The tunnel-effect contact 20 and all of the other electrically conductive contacts 26, 28, and 30 are typically formed of a bi-metal layer such as chrome-gold, as is further described in detail below.

It should also be noted that the pair of torque rebalance bridge electrodes 22 are preferably symmetrically spaced and located over opposite ends of the plate electrode 12, equidistant from the rotational axis provided by the pair of torsional flexures 16, so as to facilitate in the rebalance force linearization. Otherwise, a compensation voltage component must be added to the applied rebalance voltages in order to achieve linearization.

Referring to Figure 2, there is shown a schematic block diagram of a control system 40 for the present invention

1 tunneling sensor 10 shown in Figure 1. The control system 40 has
2 a stiff feedback loop since the relative movement between the
3 tunnel-effect tip 24 and the tunnel-effect contact 20 is
4 preferably limited to $\pm 5 \text{ \AA}$ in use. Because of the high loop
5 gain required, stability is an issue, and compensation will be
6 required to ensure phase margin near the unity loop gain
7 frequency. In accordance with the present invention, the control
8 system 40 is shown having an input acceleration 42 and an output
9 torque voltage 44 that is linearly related to the input
10 acceleration 42.

11 The control system 40 comprises an acceleration to torque
12 conversion block 46 wherein the input acceleration 42 is
13 converted into torque as a result of the pendulous nature of the
14 plate electrode 12 and the pendulous mass 18. The acceleration
15 to torque conversion is essentially realized by multiplying the
16 weight of the pendulous mass 18 by the distance between the
17 center of gravity of the pendulous mass 18 and the axis of
18 rotation running through the pair of torsional flexures 16. The
19 converted torque is summed with torque that is produced as a
20 result of the electrostatic rebalance force between the pair of
21 torque rebalance bridge electrodes 22 and the plate electrode 12.

22 The control system 40 also comprises a plate rotation block
23 50 representing the differential equation modeling the mechanical
24 motion of the tunneling sensor 10 in response to an applied
25 torque. The coefficients of M , k_D , and k_θ are the total moment
26 of inertia of the plate electrode 12 and the pendulous mass 18, a

damping spring constant, and a rotational spring constant, respectively. An angular to linear displacement conversion is performed on the output of the plate rotation block 50. θ is the angle of rotation of the plate electrode 12 in radians, and R_{tip} represents the distance from the axis of rotation running through the pair of torsional flexures 16 to the tunnel-effect tip 24.

A tip tunneling block 54 describes the current flow across the gap between the tunnel-effect contact 20 and the tunnel-effect tip 24. I represents the tunnel current, B represents a bias voltage applied across the gap, α is a constant related to the tunnel current, d is the linear displacement across the gap (θR_{tip}), and Φ represents the potential barrier to the tunnel current. The tip tunneling block 54 mathematically models the current-voltage relationship at the tunneling tip.

The tunnel current, I , is converted into a representative voltage, V , and a logarithmic amplifier 58 linearizes the exponential dependence of the tunnel current, I , on the tip displacement, d . A reference voltage, V_{ref} , corresponding to a desired quiescent point for the control loop ($I \approx 1$ nA, $d \approx 5$ -10 Å) is summed with the output of the logarithmic amplifier 58 so as to determine if any difference exists therebetween. The resultant difference signal, if any exists, is passed through an integrator 64 and a phase compensator 66 so as to provide the output torque voltage 44 which is linearly related to the input acceleration 42.

1 The force linearization block 68 utilizes the output torque
2 voltage 44 to generate the complementary rebalance voltages for
3 the pair of torque rebalance bridge electrodes 22. These
4 complementary rebalance voltages are produced by adding and
5 subtracting a constant bias voltage (V_{bias}) to the output torque
6 voltage (V_{torque}). These sum and difference voltages are then
7 applied to the pair of torque rebalance bridge electrodes 22 so
8 as to generate a rebalance torque against the plate electrode 12
9 that is proportional to $4V_{bias}V_{torque}$. Thus, the rebalance force is
10 linearly related to the output torque voltage 44, and hence to
11 the input acceleration 42. It should be noted that the voltage
12 level for the constant bias voltage (V_{bias}) is typically 10 VDC.

13 At this point it should be noted that the plate electrode
14 12, and hence the tunnel-effect contact 20, are typically
15 grounded, and a small bias voltage is typically applied to the
16 tunnel-effect tip 24. The voltage level for the bias voltage is
17 typically 0.2 VDC.

18 It should also be noted that the present invention tunneling
19 sensor 10 yields sensitivity on the order of 20 ng/V/Hz at 1 kHz.
20 According to theoretical analyses, this is substantially more
21 sensitive than mere capacitive pickoffs at this frequency.

22 The method for fabricating the present invention tunneling
23 sensor 10 is in itself novel. Figures 3-12 show cross sections
24 of the tunneling sensor 10 at sequential stages of fabrication.

25 Referring to Figure 3, the tunneling sensor 10 is shown in
26 its initial fabrication stage comprising the silicon wafer

substrate 14 that is coated on both its front and back sides with front 70 and back 72 dielectric layers, which may be silicon dioxide, silicon nitride, or silicon carbide. The preferred material for the dielectric layers 70 and 72 is thermally grown silicon dioxide.

Referring to Figure 4, the tunneling sensor 10 is shown after the front 70 and back 72 dielectric layers (hereinafter referred to as the initial oxidation, or initial oxide, layers) have been patterned using conventional photolithography and either wet or dry etching.

Referring to Figure 5, the tunneling sensor 10 is shown after a boron diffusion has been performed on selected regions 12, 76, and 78 of the silicon wafer 14 through the patterned openings in the initial oxide layers 70 and 72. The initial oxide layers 70 and 72 are used as a diffusion mask to selectively diffuse boron through the patterned openings. The boron diffusion is preferably carried out using a solid source boron diffusion at a temperature between 1100°C and 1200°C, although gas sources can also be used.

Referring to Figure 6, the tunneling sensor 10 is shown after the initial oxide layers 70 and 72 have been photolithographically removed from certain regions, such as etch slot regions 80, and from the back side of the silicon wafer 14. Also, a first bi-metal layer has been deposited by sputtering or evaporating on selected patterned regions so as to form a tunnel-effect contact 20 and various wire bond contacts, including those

1 for the plate electrode 26, the bridge electrodes 28, and the
2 tunnel-effect tip 30. This first bi-metal layer is preferably
3 chrome-gold, titanium-gold, or titanium/tungsten-gold.

4 Referring to Figure 7, the tunneling sensor 10 is shown
5 after a sacrificial (spacer) layer 74 has been deposited on
6 selected patterned regions. This spacer layer 74 may be
7 photoresist, polyimide, silicon dioxide, polysilicon, or other
8 sacrificial layers known to those skilled in the art. The
9 preferred spacer layer material is positive photoresist.

10 Referring to Figure 8, the tunneling sensor 10 is shown
11 after a thin metal (seed) layer 82 has been deposited (by
12 sputtering) over the entire front side of the wafer structure so
13 as to serve as a plating base for subsequent electroplating which
14 will form the bridge electrodes 22. This seed layer 82 must have
15 good adhesion to the various materials exposed on the front side
16 of the wafer structure, in addition to allowing easy
17 electroplating. Typically this seed layer 82 is formed of a bi-
18 metal deposit, with the first metal layer being chosen for good
19 adhesion to silicon dioxide and the second metal layer being
20 chosen for easy electroplating. The first metal (adhesion) layer
21 is typically titanium, chromium, titanium-tungsten alloy, or
22 aluminum. The second metal (electroplating) layer is typically
23 gold, chromium, copper, silver, nickel, palladium, or platinum.
24 A preferred embodiment uses a titanium-gold bi-layer as the
25 plating base (seed) layer 82.

Referring to Figure 9, the tunneling sensor 10 is shown after an electroplating mask 84 has been deposited and patterned. This mask 84 may be photoresist, e-beam resist, x-ray resist, or polyimide. A preferred implementation uses a photoresist as the plating mask 84.

Referring to Figure 10, the tunneling sensor 10 is shown after the pendulous weight 18, the bridge electrodes 22, and the tunnel-effect tip 24 have been electroplated in the open areas of the electroplating mask 84. Gold is the preferred metal for the electroplating, since gold is the preferred tunnel contact metal. Alternatively, a thin gold layer may be electroplated first, and a thicker layer of some other metal, such as nickel, silver, or copper, may be electroplated thereon. It should be noted that the bridge electrodes 22 have perforations formed therein so as to reduce the damping spring coefficient, k_b .

Referring to Figure 11, the tunneling sensor 10 is shown after the electroplating mask 84, the sacrificial (spacer) layer 74, and the exposed portions of the thin metal (seed) layer 82 have been removed by polymer stripping. The polymer stripping is typically done in photoresist stripper, acetone, or by an oxygen plasma. The portion of the seed layer 82 that is not protected by the electroplated material 18 and 24 is stripped by an appropriate wet or dry etch, such as are well known in the industry.

Referring to Figure 12, the tunneling sensor 10 is shown after an anisotropic EDP etch (ethylene-diamine, pyrocatechol,

1 and water) is preformed to substantially free up the plate
2 electrode 12. At this point, the tunneling sensor 10, which is
3 typically fabricated in an array of like sensors on the silicon
4 wafer 14, is ready for separation and packaging. Also shown is
5 the axis of rotation 86 of the plate electrode 12 running through
6 the pair of torsional flexures 16.

7 In view of the foregoing, it can be easily understood that
8 the present invention tunneling sensor 10 is smaller and easier
9 to use in common applications than the JPL device or similar
10 sensor devices. For example, the present invention tunneling
11 sensor 10 can easily fit on a 3 mm chip and can be used as an
12 accelerometer, a vibration sensor, a magnetic field sensor, a
13 pressure sensor, a hydrophone, and a microphone.

14 Also, the present invention tunneling sensor 10 requires
15 only moderate voltage levels (typically 20 volts) to achieve
16 rebalance and tip contact due to the small capacitor gaps
17 (typically 2 microns) used in surface micromachining.

18 The present invention is not to be limited in scope by the
19 specific embodiment described herein. Indeed, various
20 modifications of the present invention, in addition to those
21 described herein, will be apparent to those of skill in the art
22 from the foregoing description and accompanying drawings. Thus,
23 such modifications are intended to fall within the scope of the
24 appended claims. Additionally, various references are cited
25 throughout the specification, the disclosures of which are each
26 incorporated herein by reference in their entirety.

CLAIMS

What is claimed is:

1. A tunneling sensor with linear force rebalance, said

tunneling sensor comprising:

a plate electrode, said plate electrode being movable about an axis of rotation, said plate electrode having a first end and a second end separated by said axis of rotation, said plate electrode being unbalanced about said axis of rotation, said plate electrode having a tunnel-effect contact formed thereon;

a pair of torque rebalance bridge electrodes, a first torque rebalance bridge electrode in said pair being disposed proximate said first end of said plate electrode, a second torque rebalance bridge electrode in said pair being disposed proximate said second end of said plate electrode;

a tunnel-effect tip, said tunnel-effect tip being disposed proximate said tunnel-effect contact;

means for electrically biasing said tunnel-effect contact and said tunnel-effect tip;

means for sensing a tunnel current between said tunnel-effect contact and said tunnel-effect tip; and

feedback means for processing said tunnel current and electrically exciting said pair of torque rebalance bridge electrodes with complementary rebalance voltages derived from said processed tunnel current so as to generate an electrostatic

23 rebalance force against said plate electrode that is linearly
24 related to an imbalance force against said plate electrode which
25 is created by an acceleration thereof.

1 2. The tunneling sensor as defined in claim 1, further
2 comprising a pendulous mass, said pendulous mass being formed on
3 said plate electrode, said pendulous mass creating said unbalance
4 of said plate electrode.

1 3. The tunneling sensor as defined in claim 1, further
2 comprising a pendulous mass, said pendulous mass being formed on
3 said plate electrode, said pendulous mass contributing to said
4 unbalance of said plate electrode.

1 4. The tunneling sensor as defined in claim 1, wherein said
2 tunnel-effect contact is gold.

1 5. The tunneling sensor as defined in claim 1, wherein said
2 plate electrode is boron diffused silicon.

1 6. The tunneling sensor as defined in claim 1, wherein said
2 pair of torque rebalance bridge electrodes are symmetrically
3 spaced and located equidistant from said axis of rotation.

1 7. The tunneling sensor as defined in claim 1, wherein said
2 pair of torque rebalance bridge electrodes have perforations
3 formed therein so as to reduce a damping spring coefficient
4 thereof.

1 8. The tunneling sensor as defined in claim 1, wherein said
2 pair of torque rebalance bridge electrodes are gold.

1 9. The tunneling sensor as defined in claim 1, wherein said
2 tunnel-effect tip is disposed proximate said tunnel-effect
3 contact so as to be in line with a rotational path that said
4 tunnel-effect contact takes when said plate electrode is moved
5 about said axis of rotation.

1 10. The tunneling sensor as defined in claim 1, wherein said
2 tunnel-effect tip is gold.

1 11. The tunneling sensor as defined in claim 1, wherein said
2 means for electrically biasing said tunnel-effect contact and
3 said tunnel-effect tip comprises grounding said tunnel-effect
4 contact and applying a bias voltage to said tunnel-effect tip.

1 12. The tunneling sensor as defined in claim 1, wherein said
2 means for sensing a tunnel current between said tunnel-effect
3 contact and said tunnel-effect tip essentially comprises
4 electronic sensing circuitry.

1 13. The tunneling sensor as defined in claim 1, wherein said
2 feedback means comprises means for providing an output torque
3 voltage that is linearly related to said acceleration.

1 14. The tunneling sensor as defined in claim 1, wherein said
2 complementary rebalance voltages comprise a constant bias voltage
3 component and a torque voltage component, wherein said constant
4 bias voltage component is added and subtracted from said torque
5 voltage component so as to produce said complementary rebalance
6 voltages.

1 15. The tunneling sensor as defined in claim 1, wherein said
2 feedback means comprises means for converting said tunnel current
3 into a representative voltage.

1 16. The tunneling sensor as defined in claim 1, wherein said
2 feedback means comprises logarithmic means for linearizing the
3 exponential dependence of said tunnel current on the displacement
4 between said tunnel-effect contact and said tunnel-effect tip.

1 17. The tunneling sensor as defined in claim 1, wherein said
2 feedback means comprises reference means corresponding to a
3 desired quiescent point for said tunnel current and the
4 displacement between said tunnel-effect contact and said tunnel-
5 effect tip.

1 18. A method for fabricating a tunneling sensor with linear
2 force rebalance, said method comprising the steps of:
3 providing a substrate having an insulator formed thereon;
4 patterning said insulator and diffusing said substrate so as
5 to form a plate electrode therein;
6 depositing a tunnel-effect contact on said plate electrode;
7 electroplating a pair of bridge electrodes and a tunnel-
8 effect tip on said insulator so as to be disposed proximate said
9 plate electrode; and
10 etching selected areas of said substrate so as to free said
11 plate electrode from said substrate except for where at least two
12 torsion flexures are formed between said plate electrode and said
13 substrate thus forming an axis of rotation about which said plate
14 electrode is movable, said plate electrode thereby having a first
15 end and a second end separated by said axis of rotation, a first
16 bridge electrode in said pair being disposed proximate said first
17 end of said plate electrode, a second bridge electrode in said
18 pair being disposed proximate said second end of said plate
19 electrode, said tunnel-effect tip being disposed proximate said
20 tunnel-effect contact so as to be in line with a rotational path
21 that said tunnel-effect contact takes when said plate electrode
22 is moved about said axis of rotation.

1 19. The method as defined in claim 18, wherein said step of
2 electroplating said pair of bridge electrodes comprises
3 electroplating said pair of bridge electrodes so as to be
4 symmetrically spaced and located equidistant from said axis of
5 rotation.

1 20. The method as defined in claim 18, further comprising the
2 step of electroplating said pair of bridge electrodes so as to
3 have perforations formed therein.

1 21. The method as defined in claim 18, further comprising the
2 steps of:

3 depositing a sacrificial (spacer) layer on selected areas of
4 said substrate, said plate electrode, and said insulator; and
5 etching said sacrificial (spacer) layer so that said pair of
6 bridge electrodes span said plate electrode and a gap is formed
7 between said tunnel-effect tip and said tunnel-effect contact.

1 22. The method as defined in claim 21, further comprising the
2 steps of:

3 depositing a thin metal (seed) layer on selected areas of
4 said substrate, said plate electrode, said insulator, and said
5 sacrificial (spacer) layer; and
6 etching said thin metal (seed) layer along with said
7 sacrificial (spacer) layer.

1 23. The method as defined in claim 18, further comprising the
2 step of forming a pendulous mass on one end of said plate
3 electrode.

1 24. The method as defined in claim 18, wherein said step of
2 diffusing said substrate comprises performing a boron diffusion
3 using a solid source boron diffusion at a temperature between
4 1100°C and 1200°C.

116728

TUNNELING SENSOR WITH LINEAR FORCE REBALANCE AND
METHOD FOR FABRICATING THE SAME

ABSTRACT

1 A tunneling sensor is disclosed having a pair of force
2 rebalance capacitors that are used in a push-pull relationship so
3 as to provide a rebalance force that is a linear function of
4 applied rebalance voltages, which leads to an output voltage that
5 is linearly related to input acceleration. The tunneling sensor
6 comprises a plate electrode that is formed from and attached to a
7 silicon substrate by a pair of torsional flexures, which provide
8 an axis of rotation for the plate electrode. A pendulous mass is
9 formed on a first end of the plate electrode, and a tunnel-effect
10 contact is formed on a second end of the plate electrode. A pair
11 of torque rebalance bridge electrodes are formed on the substrate
12 so as to span the plate electrode. A tunnel-effect tip is formed
13 on the substrate so as to be proximate the tunnel-effect contact
14 and in line with the rotational path that the tunnel-effect
15 contact takes when the plate electrode is rotated.

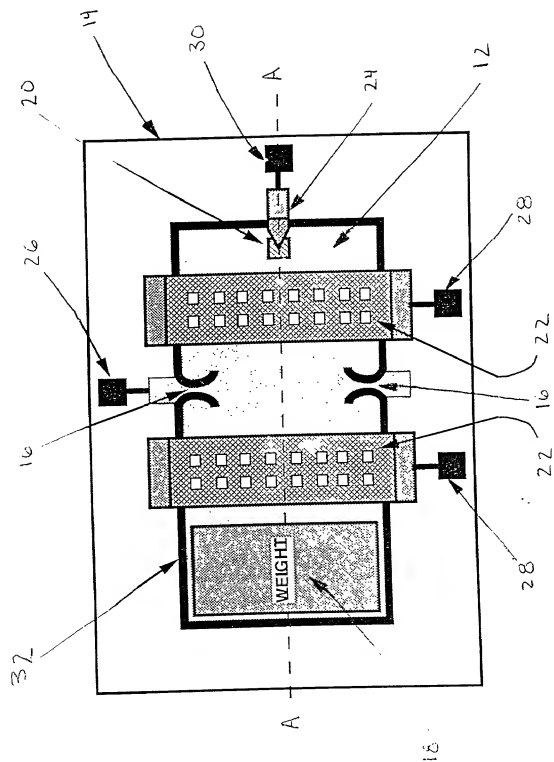


Figure 1

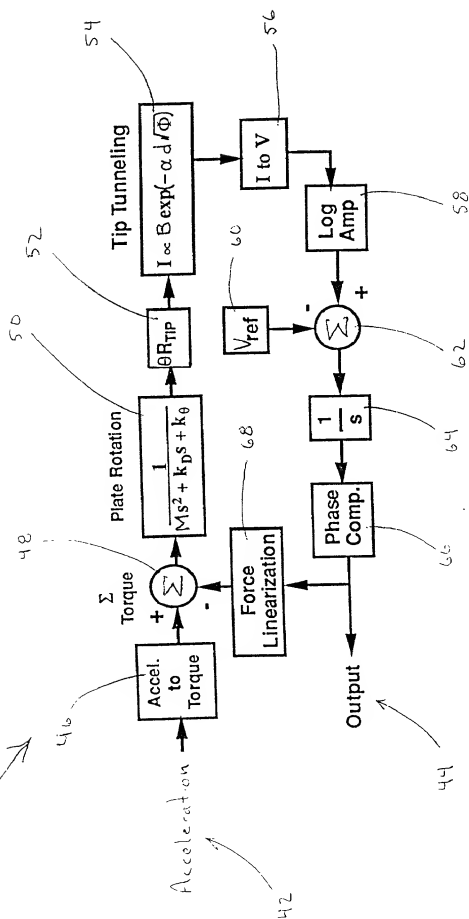


Figure 2

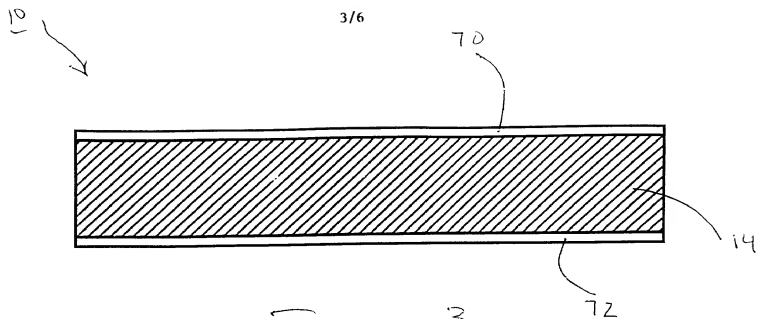


Figure 3

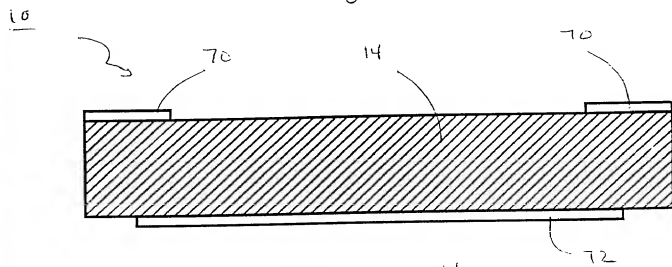


Figure 4

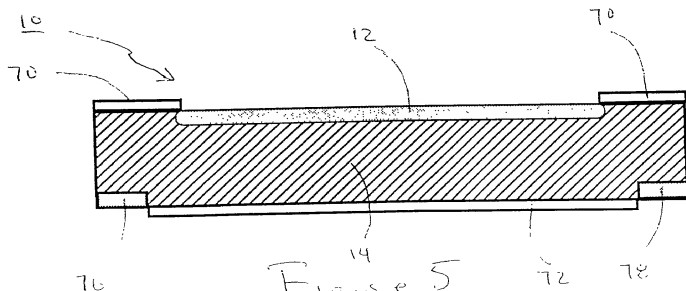


Figure 5

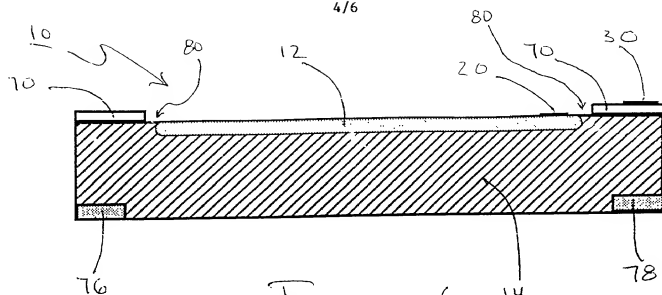


Figure 6

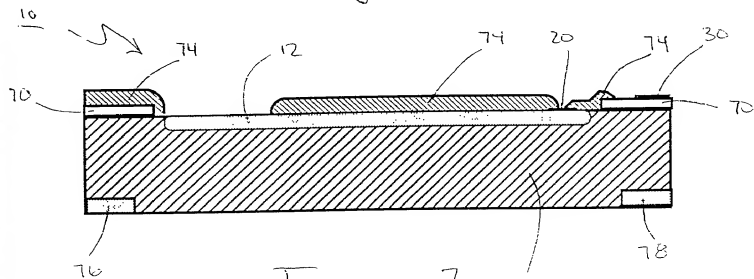


Figure 7

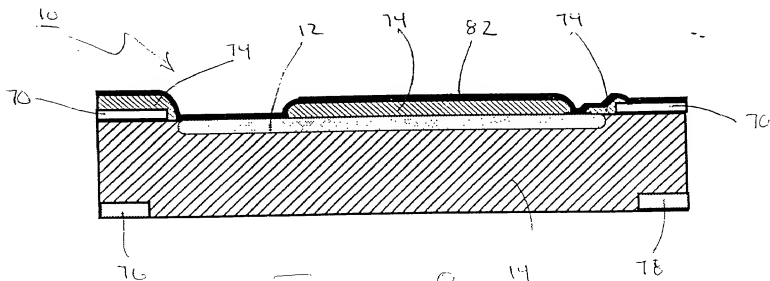


Figure 8

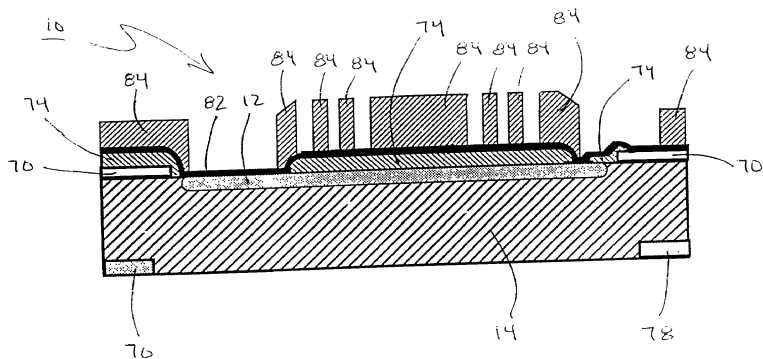


Figure 9

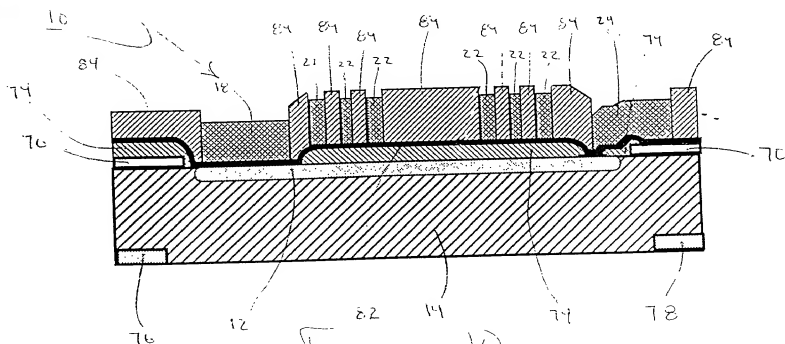


Figure 10

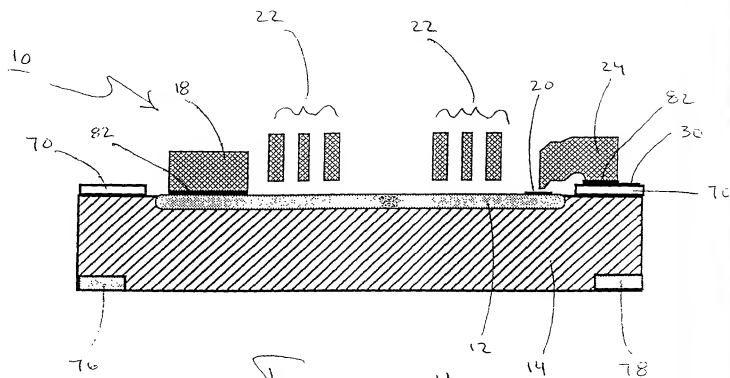


Figure 11

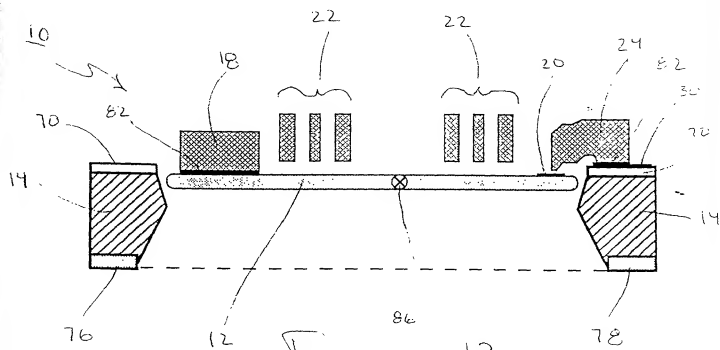


Figure 12

Attorney
Docket No.: CSDL1-453XX

DECLARATION AND POWER OF ATTORNEY

As a below-named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name;

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

TUNNELING SENSOR WITH LINEAR FORCE REBALANCE AND METHOD FOR FABRICATING THE SAME
the specification of which (check one):

☒ is attached hereto. ☐ was filed _____ as Serial No. _____,
amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations 1.56(a).

I hereby claim foreign priority benefits under Title 35, USC §119(a)-(d) of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

<u>Prior Foreign Application(s)</u>		<u>Date Filed</u>	<u>Priority Claimed</u>	
(Number) _____	(Country) _____	(Day/Month/Year) _____	<input type="checkbox"/> Yes	<input type="checkbox"/> No
(Number) _____	(Country) _____	(Day/Month/Year) _____	<input type="checkbox"/> Yes	<input type="checkbox"/> No
(Number) _____	(Country) _____	(Day/Month/Year) _____	<input type="checkbox"/> Yes	<input type="checkbox"/> No

I hereby claim the benefit under Title 35, USC §119(e) of any United States provisional application(s) listed below:

(Application Number) _____	(Filing Date) _____
(Application Number) _____	(Filing Date) _____
(Application Number) _____	(Filing Date) _____
(Application Number) _____	(Filing Date) _____

Express Mail Number

EM359608383US

Attorney
Docket No.: CSDL1-453XX

I hereby claim the benefit under Title 35 USC §120 of any United States application(s) listed below and insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35 USC §112. I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, §1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

(Application Serial No.)	(Filing Date)	(Patented/pending/abandoned)
(Application Serial No.)	(Filing Date)	(Patented/pending/abandoned)
(Application Serial No.)	(Filing Date)	(Patented/pending/abandoned)

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) to prosecute this application and transact all business connected therewith in the Patent and Trademark Office, and to file with the USRO any International Application based thereon.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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Signature: (Please sign and date in permanent ink.)

x Jonathan J. Bernstein

Date signed:

x 6 August 1996